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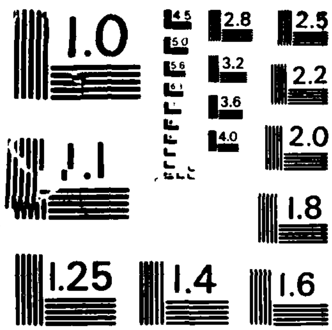

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AD-A172 477

A METHODOLOGY FOR SELECTION OF A SATELLITE SERVICING ARCHITECTURE

VOLUME I, EXECUTIVE SUMMARY

DESIGN STUDY

AFIT/GSE/85D

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A METHODOLOGY

FOR

SELECTION OF A SATELLITE SERVICING ARCHITECTURE

VOLUME I, EXECUTIVE SUMMARY

DESIGN STUDY

Presented to the Faculty of the School of Engineering

of the Air Force Institute of Technology

Air University

In Partial Fulfillment of the

Requirements for the Degree of

Master of Science

Jeffrey W. Anderson, Capt, USAF

Mark S. Gibson, Capt, USAF

Delbert B. Langerock, Capt, USAF

Richard A. Lieber, Capt, USAF

Michael A. Palmer, Capt, USAF

Michael W. Peltzer, Capt, USAF

Graduate Systems Engineering

December 1985

Approved for public release; distribution unlimited

Preface

The following report documents the design study of the Air Force Institute of Technology Graduate Systems Engineering Class of 1985. The report is in three volumes. The Executive Summary (Volume I) is a cursory review of the study and is meant to be self-contained. The Final Report (Volume II) and the Appendices (Volume III) are more detailed and should be read together for completeness. This study explains a two-phase methodology we developed to permit selection of an optimal military satellite servicing system. The work was conducted from December 1984 to December 1985. The original project concept and follow-on technical support was provided by the Rocket Propulsion Laboratory at Edwards AFB, California. Additional technical support and funding was provided by the Office for Manned Spaceflight (SD/YM) and the Office of Plans (SD/XR) at USAF Space Division, Los Angeles Air Force Station, California.

The faculty committee who assisted in this effort are:

Captain Stuart Kramer, Chairman

Dr. Curtis Spenny

Lt Col Mark M. Mekaru

Major Hugh C. Briggs

Their help in reading and helping us revise countless draft copies of this work is greatly appreciated.

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A special measure of gratitude belongs to Major Dennis Clark for his help with the optimization program, and to Major Ken Feldman for his assistance with the value system. Our heartfelt thanks also goes to Mary Peltzer and Maggie Anderson, for their assistance with revisions of this document during the final hours.

We would also like to thank the following people for their assistance and guidance with different parts of this work. Without their help, parts of this effort would not have been possible: Major Don Brown, Mr. Robert Carlton, Colonel W.H. Crabtree, Colonel Gaylord Green, Colonel Donald G. Hard, Major James K. Hodge, Lt Colonel Janson, Mr. George Lemon, Lt Colonel Eric Sundberg, Lt Colonel Joseph Widhalm, Major G. V. Wimberly, Colonel William Wittress, and Colonel William F.H. Zersen.

Captain Jeffrey W. Anderson, Project Leader

Captain Mark S. Gibson

Captain Delbert B. Langerock

Captain Richard A. Lieber

Captain Michael A. Palmer

Captain Michael W. Peltzer

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List of Tables

List of Symbols

Symbol	Description
Cr	Constraint Technique Constant
F	Feasible Region
Kg	Kilogram
Lu	Vector of Lower bounds of Control Variables
Lx	Vector of Lower bounds of State Variables
M	Maximal Eigenvalue
Mi	Initial total OSV mass
Mo	Final total OSV mass
Ms	Mass of OSV structure
P	Set of Elements Used in ISM
R	Relation
Sx	Feasible region in state space
Sz	Mapping feasible region into objective space
TOF	Time of flight for OSV mission
Ts	Synodic period
Tso	Period of the service orbit
Ttr	Period of the transfer orbit
Two	Period of the waiting orbit
U	Vector of Exogenous Variable
Ui	Exogenous Variable
Uu	Vector of Upper bounds on Control Variables
Ux	Vector of Upper bounds of State Variables

List of Symbols (Continued)

Symbol	Description
V( )	Value Function
V1	Velocity vector 1
V2	Velocity vector 2
Vpo	Velocity of parking orbit
Vtra	Velocity at apogee of transfer orbit
Vtrp	Velocity at perigee of transfer orbit
Vwoa	Velocity at apogee of waiting orbit
Wr	Weighted Technique Weight
X	Vector Of State Variables
Xi	ith State Variable
Z	Objective Function
Z	Vector of Performance Indicies
Zi	ith Performance Index
ΔVa	Delta Velocity required at perigee
ΔVosv	Delta Velocity reequired for OSV mission
ΔVp	Delta Velocity required at perigee
ΔVresupply	Delta velocity required to travel from parking orbit to service orbit. enter service orbit. and return to parking orbit
ΔVwo	Delta velocity required to get into and back out of waiting orbit
ge	Gravitational accelleration at surface of earth
pi	Element of Set P

List of Symbols (Continued)

Symbol	Description
ra	Radius at apogee of elliptical orbit
rearth	Normal radius of the earth
rp	Radius at perigee of elliptical orbit
rpo	Radius of parking orbit
rso	Radius of service orbit
tavgphase	Average time between OSV launch opportunities
tintersat	Travel time between satellites being serviced
tmaxphase	Maximum Time between OSV launch opportunities
tsatserv	Total time to service Y satellites (tservicing + tintersat)
tservicing	Time to service Y satellites

List of Abbreviations

Abbreviation	Description
AF	Air Force
CDC Cyber	Control Data Corp Cyber 175 Computer
DELIV	Delivered
DM	Decision Maker
DoD	Department of Defense
EMADAM	Extended Multi-Attribute Decision Analysis Model
EVA	Extravehicular Activity
FHG	Fixed High-G launch vehicle
FLG	Fixed Low-G launch vehicle
HLLV	Heavy Lift Launch Vehicle
HR	Hour
IC	Initial Cost
ICW	Initial Cost Weighting
ISM	Interpretive Structural Modeling
Isp	Specific Impulse of Fuel
KG	Kilogram
KTCN	Kuhn-Tucker Conditions for Noninferiority
Kg/Hr	Kilo Grams per Hour
Km	Kilometer
LEO	Low Earth Orbit
LG	Low-G launch vehicle
MADAM	Multi-Attribute Decision Analysis Model
MAUT	Multi Attribute Utility Theory

List of Abbreviations (Continued)

Abbreviation	Description
PI	Performance Index
PI	Performance Indicies
PPI	Pairwise Perferentially Independent
PROCES	Computer Program for Vector Optimization Problems
PrI	Preferentially Independent
R&D	Research and Development
REL	Reliability
RFP	Request For Proposal
RMS	Remote Manipulator System
RW	Reliability Weighting
SB	Space Base
SE	Systems Engineering
SSS	Satellite Servicing System
SUMT	Sequential Unconstrained Minimization Technique
SV	State Variable
SYS	System
TAV	Transatmospheric Vehicle
TC	Total Cost
USAF	United States Air Force
VOP	Vector Optimization Problem
WDI	Weak Difference Independent

Abstract

A two-phase methodology for selecting an optimal military satellite servicing system is developed using the systems engineering approach. This methodology is used to evaluate several alternative systems at varying levels of detail. The candidate systems are composed of low-G launchers, high-G launchers, orbital servicing vehicles, and space bases. An optimal realization is then derived for a system of low-G launchers and orbital servicing vehicles. In the first phase of the approach, vector optimization techniques are used to vary the states of a model to obtain a set of optimal solutions. The second phase embodies the decision maker's preferences in a value system to enable preference ranking of the optimal solutions in the non-dominated solution set. This methodology, as presented, can be applied to any complex problem with multiple conflicting objectives. It is designed for use by an engineering organization supporting a senior-level decision maker.

ES. Executive Summary

ES.1 Introduction

The issue of satellite servicing is complicated, having many economic and political overtones. The basic fact is that satellites cost a lot of money. Once placed in orbit, the failure of any number of subsystems can make a satellite useless. Until recently, the United States was unable to retrieve malfunctioning satellites, and failed satellites were considered a total loss. However, demonstrations using the space shuttle have proven that on-orbit servicing and repair of satellites is now possible.

The National Aeronautics and Space Administration (NASA) and the Air Force have both made commitments to make their satellites serviceable. As a result of the United States Spacecraft Maintenance Policy Review Study (Dept. of AF, 1984), the Undersecretary of the Air Force for Research and Development directed that:

> The Air Force policy is to ensure that spacecraft maintenance options are considered in requirements definition, acquisition program management, and contractual documentation for those satellite programs wherein these options might be reasonably implemented. The Air Force should actively examine the utility of spacecraft maintenance options (particularly preventative maintenance, refueling and repair) and avoid, wherever practicable, design actions which would appear to preclude on-orbit maintenance later in the spacecraft life cycle (Aldridge, 1984).

In May 1985, the USAF Space Division issued a Request For Proposal (RFP) for contractors to develop alternatives for a Space Transportation Architecture. As stated in the statement of work portion of the RFP:

> The primary objectives of this study are to (1) determine the overall space transportation architecture(s) and transportation systems that can effectively perform future DoD and NASA missions projected for the 1995 through 2010 time period, (2) identify the enabling technologies required for future space transportation systems and prepare an integrated plan to develop these technologies, and (3) refine the mid-1990's transportation system concept(s), and prepare preliminary system specifications and special engineering plans for refined concept(s) to facilitate the start of Validation Phase (Space Division, 1985).

Air Force organizations are serious about finding cost effective ways to accomplish their mission in space. Satellite servicing may play an important role in that architecture, either from a cost standpoint or as a mission necessity. If the Strategic Defense Initiative is implemented in a space environment, then there will probably be mission requirements for reservicing weapon system resources depleted by periodic testing, use, or leakage. Now is the time to start considering how an efficient, low-cost servicing architecture could be included in an overall transportation infrastructure.

ES.2 Problem Definition

The primary objective of a satellite service system is to deliver mass from earth to orbit, and then on to the satellites. There are numerous ways this could be accomplished, as illustrated by Figure ES.1. First, consider moving the mass from earth to orbit. The launch site could be a fixed point with permanent support facilities, or a mobile launcher using portable or existing support facilities. For flexibility and survivability, one might want the mobile launchers. However, this might undesirably increase costs over a system using fixed launch sites. Once the mass is in orbit, it must be distributed to the satellites. It may be desirable to have a space depot in orbit to allow the off-loading of supplies. This space depot could act as a warehouse or a repair center to allow more flexible scheduling and support of orbital servicing vehicles. Maintaining supplies in space also protects the system from temporary loss of launch systems. However, having a space depot involves more cost and could raise political issues. This shows that to accomplish the primary objective of servicing satellites, many conflicting sub-objectives must be satisfied.

The objective of this study is to select the best system to service satellites. If this problem involved only

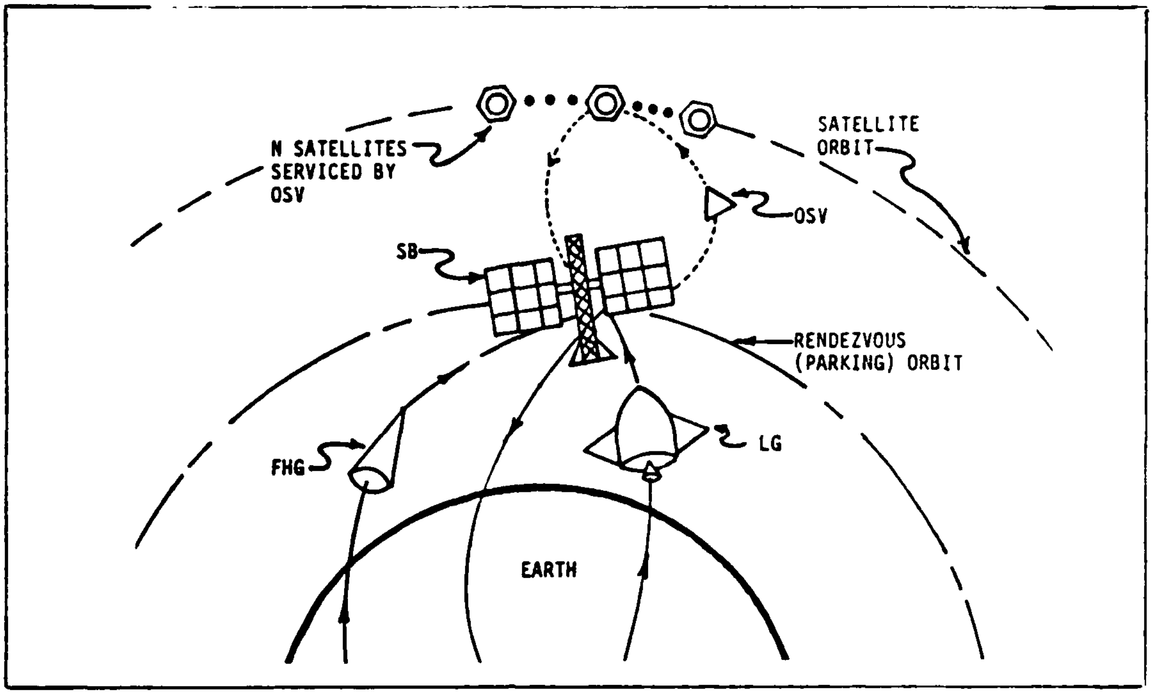


Figure ES.1 Possible Scenario

a single objective, it would be a simple scalar optimization problem with a single answer. However, since it involves multiple conflicting objectives, no single solution dominates all the others using objective criteria. When a problem has conflicting objectives, the "solution" is a set of equally optimal realizations or designs. This set of designs is called the non-dominated solution set (NDSS). The NDSS can be thought of as forming an "efficient frontier" which represents the optimal trade-offs between the conflicting objectives.

Table ES.1 lists several examples of the conflicting objectives whose satisfaction would result in accomplishing the overall objective of servicing satellites. One way to

select the best system, using the basic objectives of Table ES.1, is to extract the maximum performance from a system at the minimum possible cost. Performance could be indicated by measuring the mass delivered to orbit, and system reliability, while cost could be broken down into initial costs and operating costs.

Table ES.1

Basic Objectives

Minimize Costs	Maximize Performance
Operating Cost per Year	Mass of Payload Delivered to Orbit
Initial Cost	Reliability

A common structural formulation for the sub-objectives of a multi-objective problem is a hierarchy tree (see Figure ES.2). The advantage of formulating the objectives into a hierarchy tree is that it shows how the satisfaction of the subobjectives leads to the satisfaction of the overall objective.

Every decision maker will have different preferences for satisfying these conflicting objectives. In selecting an optimal solution for implementation, one decision maker may favor a solution that has low operating costs with minimal mass of payload delivered to orbit. Another

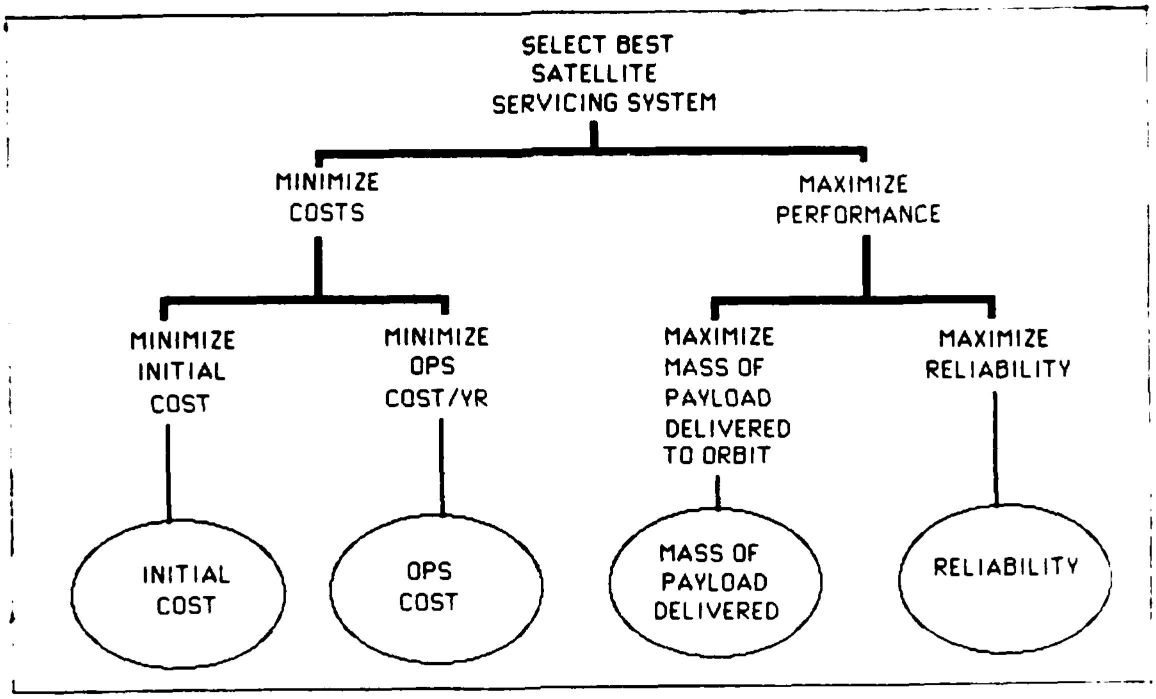


Figure ES.2 Hierarchy Tree of Objectives

decision maker may favor maximum payload delivered to orbit in spite of the costs. Consequently, the decision making process is volatile.

ES.3 Solution Strategy (Methodology)

In this study, the systems engineering approach was used to develop a two-phase methodology to deal with this volatility in the decision making process. The first phase involves the engineering design portion of the project, which uses strictly objective criteria to generate a set of optimal candidate solutions. It is normally very time-intensive, and consequently expensive. The second phase uses the preferences of the decision maker to

rank-order the set of solutions. In addition, it provides explicit information on the effects of the decision maker's preferences, and the trade-offs possible by changing those preferences. Then, if external conditions or personal reevaluation cause a decision maker's preferences to change, the first phase does not need reaccomplishment.

The two phases of the methodology can be broken down into six steps as shown in Table ES.2. The steps are problem definition, design of a value system, synthesis and modeling of alternative solutions, analysis and validation of those solutions, alternatives ranking and selection of an appropriate solution, and planning for future actions.

Table ES.2

Steps of Two Phase Methodology

Phase I	Phase II
o Problem Definition	
	o Value System Design
o Systems Synthesis And Modeling	
o Systems Analysis	
	o Decision Making
	o Planning For Action

ES.3.1 <u>Problem Definition Step.</u> Problem definition is the key initial step in the systems engineering approach. In this step, the framework for the rest of the process is set. Considerable care must be taken to ensure that the "real" problem is identified and addressed. It is also important to determine not only the overall problem or goal, but also the decision situation that brought about consideration of this problem. Other factors requiring identification during this step include: the "actors" involved in the problem, what factors can and cannot be controlled, and the likely system inputs and desired outputs.

Flexibility is necessary during this step, since knowledge gained during later iterations should be used to modify the problem definition when appropriate. The first attempt at the problem definition is usually rather abstract; necessary details can be added on later iterations. Also, the analyst should periodically ask the decision maker to confirm that the problem definition formulated addresses the problem of interest.

ES.3.2 <u>Value System Design Step</u>. Value system design is the first step of the volatile second phase of the systems engineering two-phase methodology, following the problem definition step. It does not need to precede the other

steps of the first phase. However, if it is accomplished before the remaining steps of phase one, much time will be saved.

The design of the value system in a complex problem usually begins with the creation of a hierarchy tree of objectives. The decision situation or overall objective is placed at the top of the tree. Objectives whose accomplishment would lead directly to satisfying the overall objective are placed at the second level of the tree. Usually, these high level objectives cannot be measured to indicate their level of accomplishment. Therefore, these second level objectives are furthur subdivided until a level is reached where the attainment of an objective can be directly measured. These measures of performance, or performance indices, indicate the relative level of achievement of the objectives. Since there is no unique hierarchy of objectives for a problem, the analyst should have the decision maker approve the final hierarchy.

The level of objective attainment measured by each performance index at the bottom of the hierarchy tree will be different for each candidate solution in the NDSS. Consequently, every decision maker will prefer one solution over another, based either on established policies, or on personal biases from his own experiences. The value system is designed to represent these preferences in a mathematical

fashion. It provides an organized method for ranking a set of otherwise equally optimal solutions according to the decision maker's preferences.

ES.3.3 System Synthesis and Modeling Step. Identification or creation of alternative solutions is the second step of the engineering design phase (phase one). This step involves defining candidate solutions to the problem. describing these candidates, and measuring the performance of each candidate against the objectives. This is termed system synthesis (Sage, 1977:73). During the problem definition step some of the potential candidate solutions will be identified. However, it is desirable to include as many candidate solutions as possible, to prevent overlooking the true optimal solution. candidate. Brainstorming is an excellent technique for a first attempt at generating solutions. (Sage, 1977:167-176) describes the merits of using brainstorming, brainwriting, and Delphi techniques for generation of ideas in a group. These techniques can be used to identify additional and innovative ways to accomplish the objectives defined in the problem definition. Since this methodology uses an iterative approach and optimizes the candidates that are generated, unworkable ideas will quickly fall out.

Once a set of candidates has been generated, some method of describing and analyzing these alternatives must

be used. Typically, the different system alternatives are described in terms of a model. In its most general definition a model is "a representation of a system which can be used as an explanatory device, an analysis tool, a design assessor, or even a crystal ball." (Pritsker, 1984) A model should describe and differentiate between proposed systems while predicting the performance of each. The form of the model must be such that analysis techniques can be used to answer predetermined questions. In this study, one such question is, "What are the trade-offs that can be made between the number and types of subsystems, and what effect does this have on the overall system performance?" Physical and graphical models are inadequate to answer this question. Physical models are too expensive to build for every possible alternative satellite servicing system, and graphical models do not allow any flexibility in controlling the environment or in varying the model attributes. Mathematical (analytical or simulation) models, however, do have the flexibility and cost effectiveness that is needed for this study.

ES.3.4 Systems Analysis Step. During this step of the methodology, the candidate system models are analyzed to yield optimal engineering solutions. This analysis consists of two parts: generation of the members of the NDSS, and validation of those results. Multi objective optimization

theory (MOOT) techniques are used to generate the non-dominated solutions for this study. The resultant NDSS is then analyzed to determine the validity of the models and the results.

For the problem of selecting an optimal satellite servicing system, MOOT techniques were found to be the most helpful tool for analysis. Using MOOT, an optimizer algorithm, PROCES, uses the model to generate an optimal trial solution. This trial solution is then compared against the members in the non-dominated solution set. If the trial solution is not dominated by any other solution, it is added to the NDSS. Eventually a set of non-dominated solutions is created that covers the feasible range of designs for each modeled system.

Once an NDSS is generated, the validity of the solutions must be confirmed. Sensitivity analysis is one of the most powerful methods used for checking the validity of the system models and solutions. By analyzing the solutions in the NDSS, the analyst can determine potential problems with the model or the optimizer algorithm. Identified problems are corrected and the entire process is then repeated. This iterative approach permits early identification of flaws in the model or in the optimizer, enabling better solutions with each iteration. Since a model cannot perfectly duplicate the real world, there will

always be a certain amount of error or uncertainty associated with the solutions. Sensitivity analysis identifies the impacts of the uncertainties that remain.

ES.3.5 Decision Making Step. The decision making step, along with the design of the value system, is the bulk of the second phase of the systems engineering approach. Alternative system descriptions have been modeled, the models have been validated and analyzed, and a set of nondominated "equally-optimal" solutions have been found. Now the members of the NDSS must be ranked according to the subjective preferences of the decision maker, and the most preferred solution identified.

Each member of the NDSS represents and describes a different realization (i.e. a particular design) for one of the candidate solutions modeled in the systems synthesis and modeling step. These solutions are equally optimal using only objective criteria. However, with all other performances being equal, one system description may cost more for operations, or one may have higher reliability. Consequently, a decision maker will prefer one solution in the set over the others. The systems engineering approach allows a supporting engineering organization to provide not the solution, but a set of optimal solutions for consideration by the decision maker. Selection of a solution is described by DeNeufville and Stafford (1971:12)

to be

> "by definition, not a technical problem alone. The analysts' role is precisely that of helping the decision process by removing as many of the technical uncertainties as possible ... systems analysis is fundamentally an attempt to define issues and alternatives for the decision maker and then to provide him with the information relevant to his choice."

The value system is simply a mechanism that captures the decision maker's preferences for incorporation into the solution process. The decision maker's utility for the performance measures is multiplied by the weighting preferences of the objectives in the hierarchy tree and summed. This yields a single figure of merit which represents the decision maker's preference for each solution in the NDSS. The different solutions in the NDSS can then be rank-ordered by their associated figures of merit. It is also helpful for a decision maker to know how sensitive the solution ranking is to changes in his preference weightings. A robust solution which may not have been ranked the highest may be a more advantageous selection, especially if there is uncertainty in some of the system parameters.

ES.3.6 Planning for Action Step. Planning for action is directly tied in with decision making. In this step the analyst examines the progress taking place in the solution process, and decides what refinements are needed and to what

degree. Since the same six steps are repeated, the action taken here may vary with each iteration. Early in the design, the usual action is to continue with greater detail through a new iteration, incorporating the results of past iterations. The new iteration should correct areas of uncertainty that were uncovered, while continually working towards a better answer. After the process has converged to a satisfactory set of solutions, the analyst may use this step to plan how to communicate the results to the decision maker. Once the decision maker has the results, his decisions will drive future actions on the project. These actions might include furthur iterations to provide more detail, implementation of the chosen design, or shelving of the project.

This sequence of steps is performed iteratively, as diagrammed in Figure ES.3, until one is satisfied that the process has converged to a solution. Notice that phase two does not depend on completion of phase one. It is recommended that the design of the value system be started immediately after the problem is defined. This permits the same objective structure used in the value system to define the objectives for modeling the solutions.

The iterative nature of this two-phase methodology allows knowledge gained during early iterations through the methodology to be used in improving the solutions in later

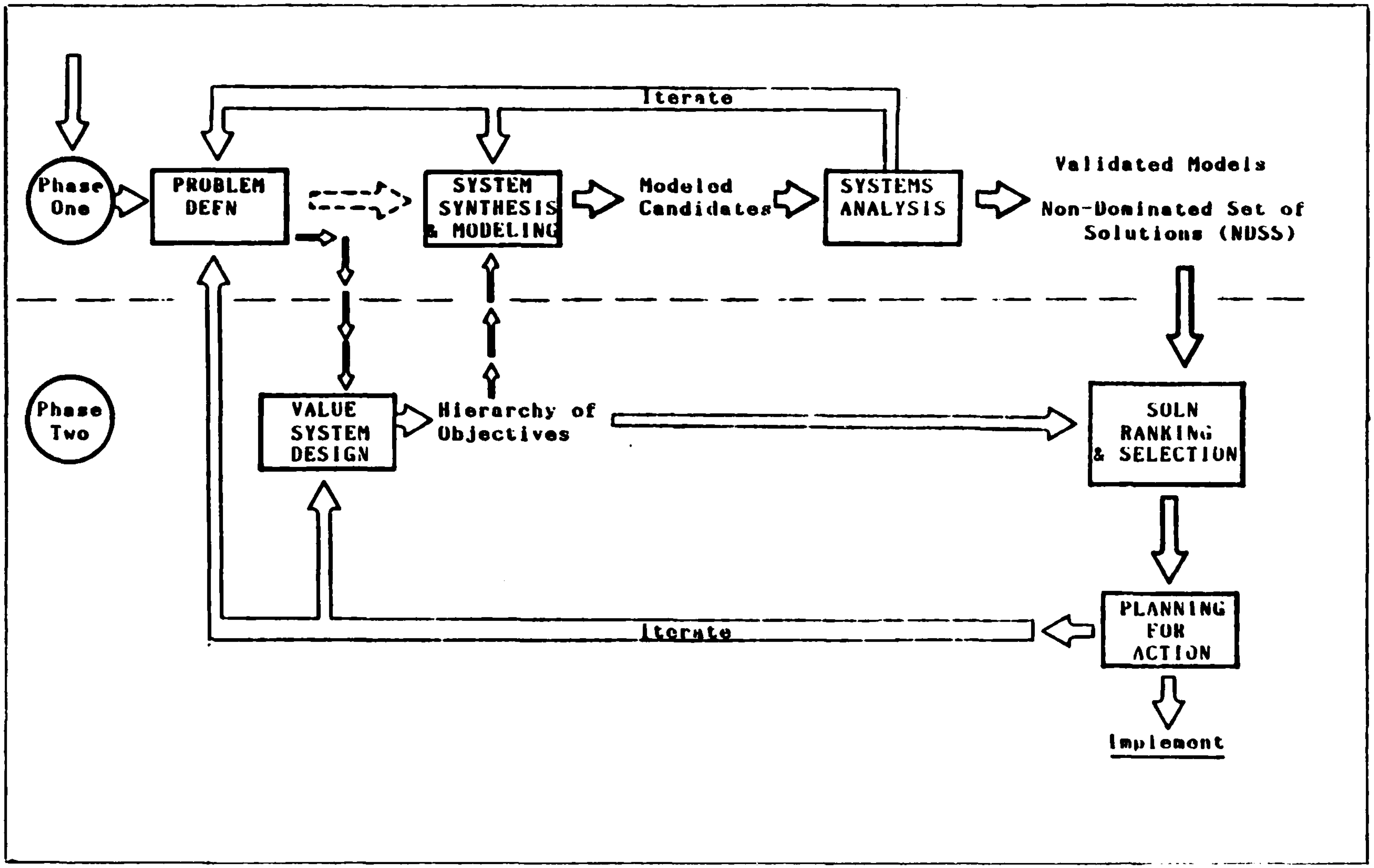


Figure ES.3 Two Phase Methodology Block Diagram

iterations. Using the systems engineering approach, a crude solution is found early (represented by the first peak of the curve in Figure ES.4). As more is learned through each subsequent attempt, the iterations converge to a set of optimal final solutions. This is in contrast to the traditional engineering approach which tends to seek a straight line solution over time. It does not approach an answer until late in the design when subcomponents which have been optimized are fit together. In the systems engineering approach, mistakes and dead ends are recognized early, thus saving manpower and money -- an obvious advantage over the traditional approach.

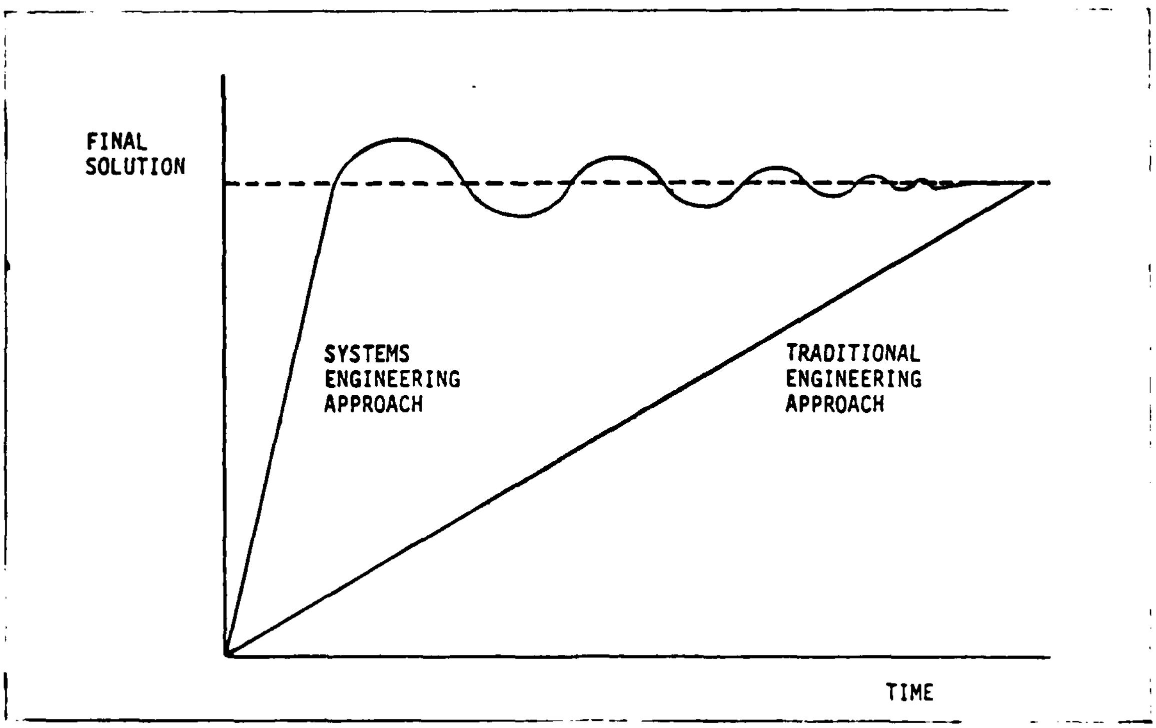


Figure ES.4 SE Approach vs Traditional Engineering Approach

ES.4 Application to Satellite Servicing

The systems engineering methodology described in section ES.3 was applied to the problem of selecting a satellite servicing system architecture. The details of tailoring the SE method to this problem are described in the following sections. Since the problem statement has already been discussed, we will begin with value system design and follow the methodology through to the decision making step.

ES.4.1 Value System Design. Because every decision maker has different preferences, every decision maker has a unique value system, which is simply a formal, mathematical representation of his preferences. If certain axioms are met, a mapping of those preferences to a value scale can be accomplished. Using these mappings, an analyst can then rank the solutions to the problem in order of preference based on the information obtained from the decision maker.

In situations where there is uncertainty involved with the alternative solutions, the mapping is referred to as a utility function. For functions where the choices involved are strictly deterministic, the mapping is called a value function. The two most common forms of these functions are the additive and multiplicative forms. The appropriate form to use in a problem is identified by satisfying certain necessary and sufficient conditions of independence among

the objectives of the problem. Often the objectives in a complex problem are conflicting, and the decision maker will likely have different preferences for each of those objectives.

A common structural formulation for the objectives in a multi-objective problem is in the form of a hierarchy tree as shown in Figure ES.5. A hierarchy tree enables one to see how satisfaction of the subobjectives leads to the satisfaction of the overall objective. By accomplishing pairwise comparisons between objectives at each level of the tree, the decision maker can indicate to the analyst what his preferences are for each of the objectives in the problem.

Each candidate solution for the problem will have a different level of accomplishment for each of those objectives. The value system then allows the analyst to use the decision maker's preferences for the different objectives along with the level of accomplishment of those objectives from each solution to obtain a rank-ordering of the possible solutions. The decision maker can then select the solution that best suits his purposes.

In creating the objective or hierarchy tree, the analyst and decision maker continue to define subobjectives until a level is reached where accomplishment of the

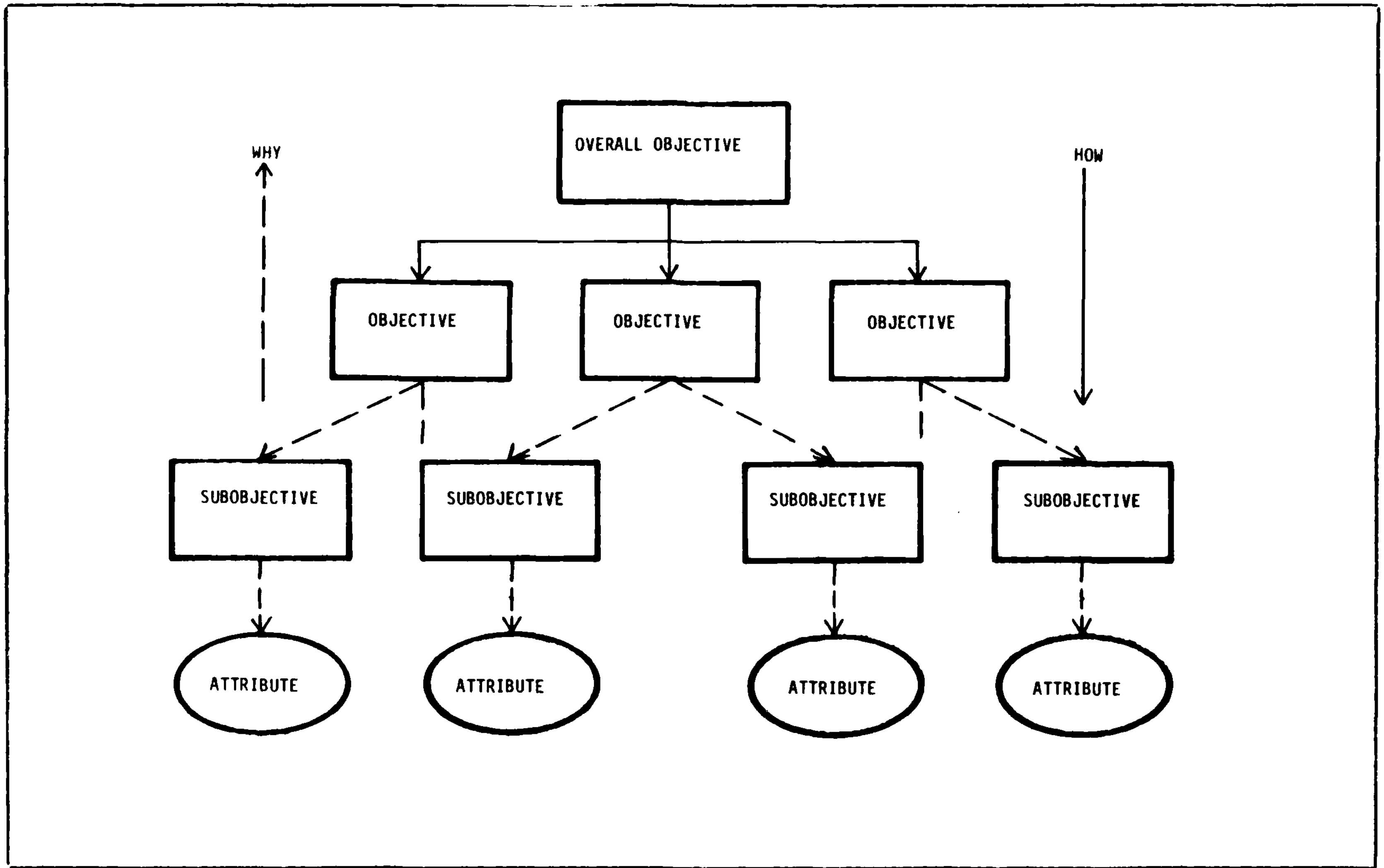


Figure ES.5 Hierarchy Tree of Objectives

subobjective can be measured in some way. These measurable entities (represented by the ovals in Figure ES.5) are called attributes or performance indices, since they enable one to see how well the objectives are being satisfied. Each one of these performance indices has an associated value function (or utility function). This function, which has values between zero and one, describes the utility that the decision maker places on the range of measure of that attribute. For example, consider the performance index initial cost, which would likely be measured in dollars. Every decision maker will have a different function that maps his preferences associated with the given range of dollars to a value scale. It might be a simple linear function, indicating that the decision maker has a straight-line preference for fewer dollars of initial cost versus more dollars of initial cost. However, the value function could have any shape, logarithmic or exponential, for example. Whatever its shape, it maps the decision maker's preferences for the range of the performance index to a dimensionless value scale.

For each candidate solution, the analyst can then use the various value scales to obtain "values" for the levels of accomplishment of the various attributes. Using these "values", and knowing the decision maker's preferences for the different objectives in the hierarchy tree, the analyst

can determine a single figure of merit that then represents the preference the decision maker has for that solution. This process is repeated for each candidate solution. resulting in a single figure of merit that represents each solution. The analyst can then rank all the solutions based on these figures of merit to create a listing of solutions ranked in preference order. This is very effective and time-efficient. especially when the list of candidate solutions is a large one.

In this study. the hierarchy tree in Figure ES.6 was used as a simple list of objectives. Preference weightings were determined by having decision makers perform pairwise comparisons between objectives at each level of the tree. as the example in Figure ES.7 demonstrates. A matrix is then formed with the rows and columns representing the different objectives at a particular tree level. The entries in the matrix are the comparison numbers taken from the comparison scale. as seen in Figure ES.8. Note that the matrix is inverse-symmetric to account for the inverse comparisons. Using a technique developed by Thomas Saaty from the University of Pennsylvania. the preference weightings for each tree level corresponds to the normalized eigenvector for the maximal eigenvalue of the matrix. This technique is used to determine the preferences for the objectives at each level of the hierarchy tree.

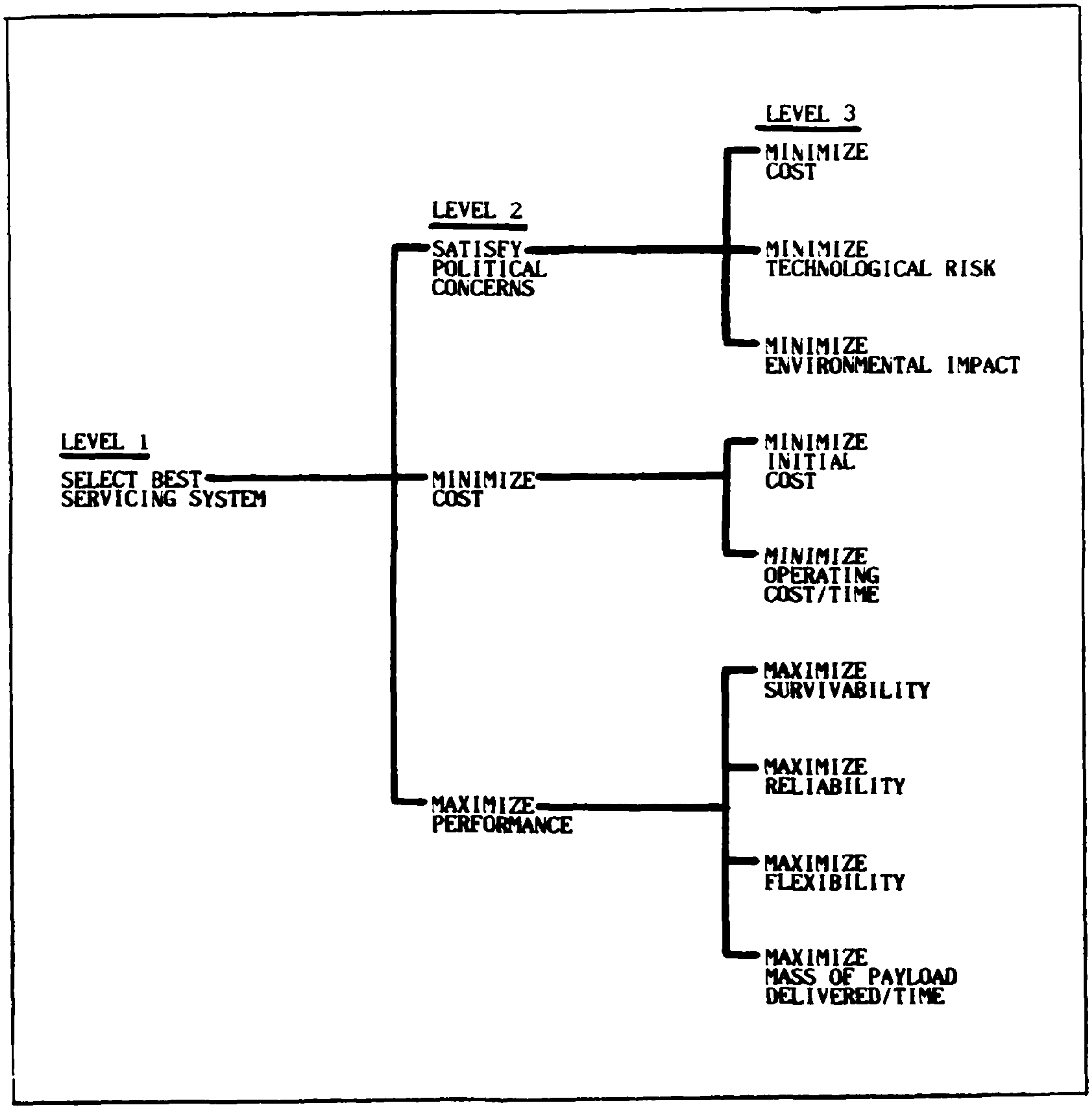


Figure ES.6 Hierarchy Tree

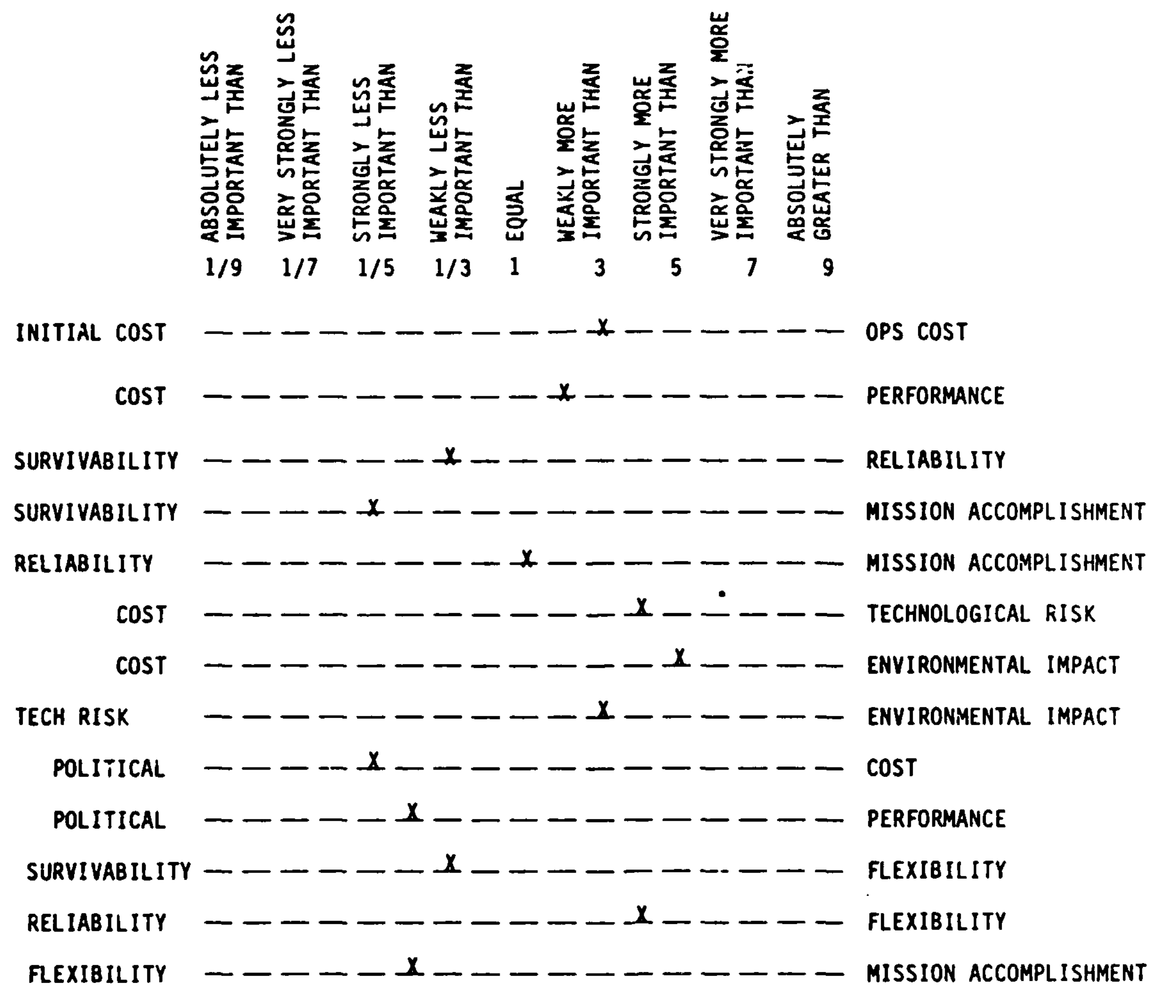


Figure ES.7 Pairwise Comparison Example

$$\begin{array}{l} \\ \text{COST} \\ \text{TECH RISK} \\ \text{ENVIRONMENT IMPACT} \end{array} \begin{array}{c} \begin{array}{ccc} \text{COST} & \text{TECH RISK} & \text{ENVIR IMPACT} \end{array} \\ \begin{bmatrix} 1 & 4 & 5 \\ 1/4 & 1 & 3 \\ 1/5 & 1/3 & 1 \end{bmatrix} \end{array}$$

Max Eigenvalue 3.086
Normalized Eigenvector 0.6738, 0.2255, 0.1007

$$\begin{array}{l} \\ \text{INITIAL COST} \\ \text{OPS COST} \end{array} \begin{array}{c} \begin{array}{cc} \text{INITIAL COST} & \text{OPS COST} \end{array} \\ \begin{bmatrix} 1 & 3 \\ 1/3 & 1 \end{bmatrix} \end{array}$$

Max Eigenvalue 2.000
Normalized Eigenvector 0.75, 0.25

$$\begin{array}{l} \\ \text{SURVIVE} \\ \text{RELIAB} \\ \text{FLEX} \\ \text{MASS P/L DELIVER} \end{array} \begin{array}{c} \begin{array}{cccc} \text{SURVIVE} & \text{RELIAB} & \text{FLEX} & \text{MASS P/L DELIVER} \end{array} \\ \begin{bmatrix} 1 & 1/3 & 1/3 & 1/5 \\ 3 & 1 & 4 & 1 \\ 3 & 1/4 & 1 & 1/4 \\ 5 & 1 & 4 & 1 \end{bmatrix} \end{array}$$

Max Eigenvalue 4.190
Normalized Eigenvector 0.079, 0.3737, 0.1359, 0.4114

$$\begin{array}{l} \\ \text{POLITICAL} \\ \text{COST} \\ \text{PERFOR} \end{array} \begin{array}{c} \begin{array}{ccc} \text{POL} & \text{COST} & \text{PERFOR} \end{array} \\ \begin{bmatrix} 1 & 1/5 & 1/4 \\ 5 & 1 & 2 \\ 4 & 1/2 & 1 \end{bmatrix} \end{array}$$

Max Eigenvalue 3.025
Normalized Eigenvector 0.09739
0.5695
C.3331

Figure ES.8 Decision Maker Comparisons in Matrix Notation

The objectives in this hierarchy tree were found to satisfy the independence conditions for an additive value function. This makes the task of finding a figure of merit much simpler. It allows the analyst to simply multiply the "value" of the performance index (obtained from the value function curve - see sample in Figure ES.9) by the preference weighting for the objective that the attribute measures and sum the results at the tree branch. The result is multiplied by the preference weighting at the next level of the tree and summed to the results from the other branches. This is continued until a single number is obtained at the top level of the hierarchy tree. This single number is the figure of merit for that solution.

ES.4.2 System Synthesis and Modeling. The purpose of modeling a service system is to describe it in such a way as to distinguish between candidate system designs and evaluate the performance of each design in terms of achieving the desired system objectives. The approach used in this study was to establish analytical equations as a means of connecting system design parameters to the desired system attributes. Based on the four system objectives at the base of the hierarchy tree in Figure ES.2, and other factors such as flexibility and survivability, the conceptual models depicted in Figure ES.10 were developed.

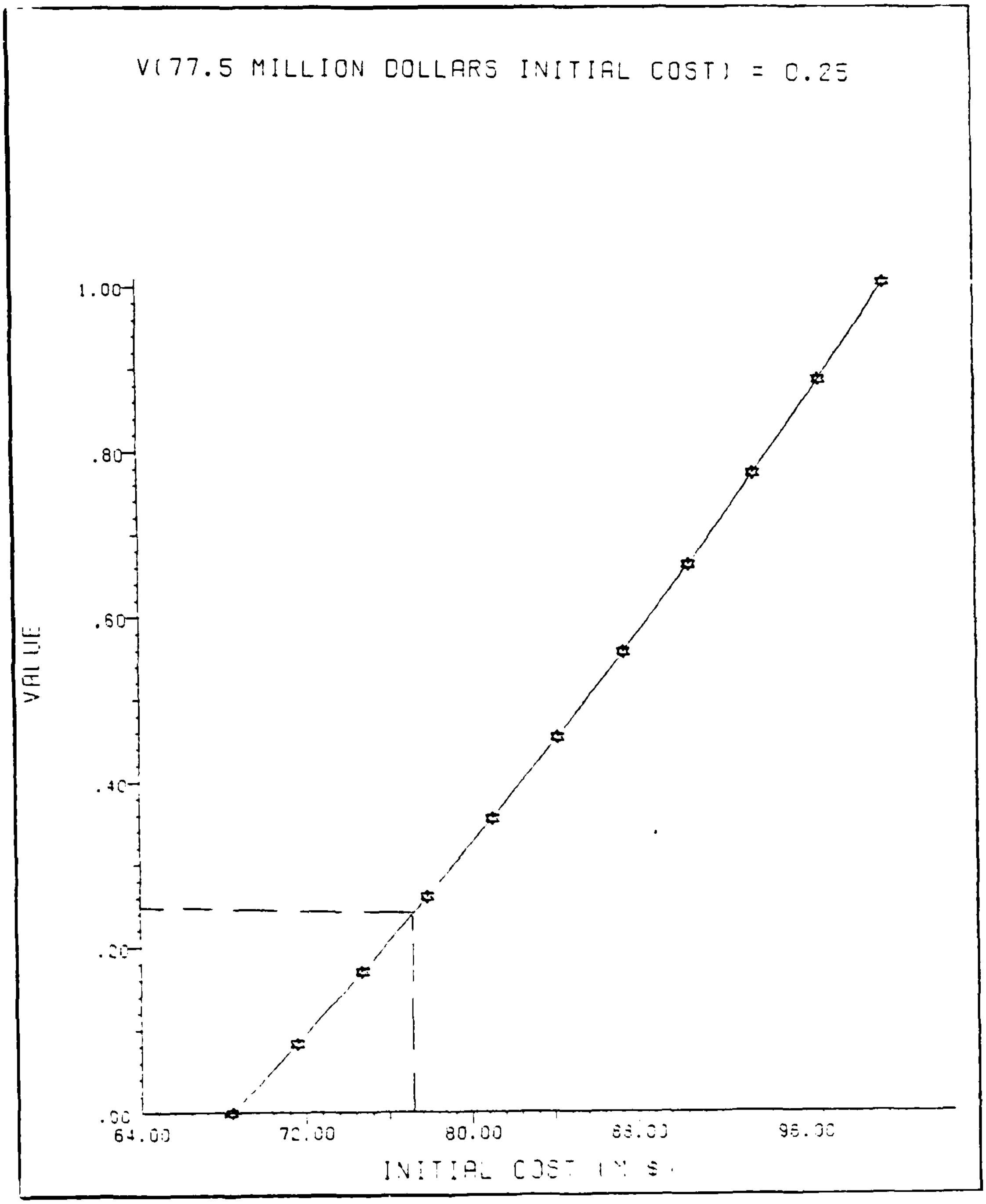


Figure ES.9 Sample Value Function Curve

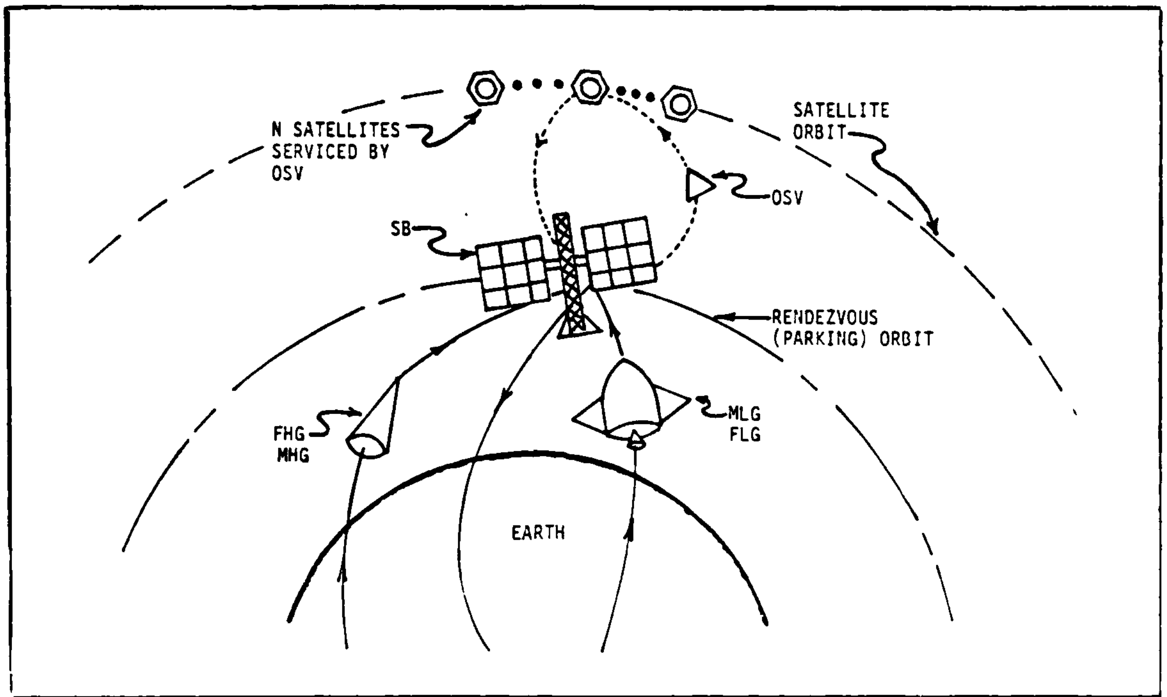


Figure ES.10 Conceptual SSS Models

The mission of the SSS is divided into two functional areas: (1) deliver mass from earth to orbit and (2) deliver mass from orbit to the satellites needing service. A total of six subsystems were defined to perform the two functions. Figure ES.11 describes these subsystems.

For the first functional area, four launch subsystems are catagorized by the type of mass that they can carry and the type of launch site they can use. The payload mass is identified as being either fragile or durable. Fragile mass cannot withstand high acceleration forces, and might consist of sensitive electronic spare parts or people. Durable mass

MISSION FUNCTIONS

- o MASS TO ORBIT (LAUNCH SUBSYSTEMS)
  - TYPES OF MASS LAUNCHED
    - -- FRAGILE OR DURABLE
  - TYPE OF LAUNCH SITE
    - -- MOBILE OR FIXED

  FLG - FIXED LAUNCH SITE - LOW-G
  -- SHUTTLE TYPE

  MLG - MOBILE LAUNCH SITE - LOW-G
  -- TAV TYPE

  FHG - FIXED LAUNCH SITE - HIGH-G

  MHG - MOBILE LAUNCH SITE - HIGH-G

- o MASS FROM ORBIT TO SATELLITE (SERVICE SUBSYSTEMS)

  SB - SPACE BASES
  -- FIXED ALTITUDE
  -- FIXED INCLINATION

  OSV - ORBITAL SERVICE VEHICLE
  -- CHANGE ALTITUDE
  -- CHANGE INCLINATION

Figure ES.11 Mission Functions and Subsystems

is not affected by high-G loads, such as fuel and structural parts. Thus, low-G launch subsystems provide the means to carry required sensitive electronics and man into space, while high-G launch systems are envisioned to provide a swift and economical means of transporting large amounts of durable mass into orbit.

Because of strategic considerations, launch sites are identified as being either fixed or mobile. Launches from fixed sites do not vary geographically, and are therefore susceptable to terrorist attack. However, launches from mobile sites are far less predictable, and therefore provide a higher degree of survivability and flexibility. With these definitions, the four launch subsystems are:

- Fixed Low-G (FLG) launch system. The NASA space shuttle is an example of an FLG.

- Mobile Low-G (MLG) launch system. The Trans-Atmospheric Vehicle (TAV) under study (Covault, 1985) could be such a launcher.

- Fixed High-G (FHG) launch system. Envisioned by an L-5 Society member (Eklund, 1984), a hydrogen blast tube that propels canisters into orbit could be an FHG.

- Mobile High-G (MHG) launch system. A physical example of such a system could not be determined at this time.

For the second functional area of moving mass from orbit to the satellites, two service subsystems are defined. The space base (SB) is a manned or unmanned structure in a fixed earth orbit. It can act as an orbital warehouse of satellite spare parts, or as a refurbishing hanger for the second service subsystem. The orbital servicing vehicle (OSV) is a spacecraft, either manned or robotic, designed to change orbital altitude and inclination in order to deliver mass to satellites. Once at the satellite, robots or man would perform the necessary servicing function. Thus, the two service subsystems are:

- Space Base (SB). The NASA space station is an example of an SB.

- Orbital Servicing Vehicle (OSV). Potential concepts under study by NASA include the robotic Orbital Maneuvering Vehicle or OMV (Nasa, 1985) and the manned or unmanned Orbital Transfer Vehicle or OTV ("Aerospace", 1982).

By combining various launch and service subsystems, 45 different conceptual architectures for a SSS can be defined. Using analysis techniques described in Chapter IV,

Volume II of this report, four conceptual models were chosen for analytical equation development. These models are listed in the first column of Figure ES.12.

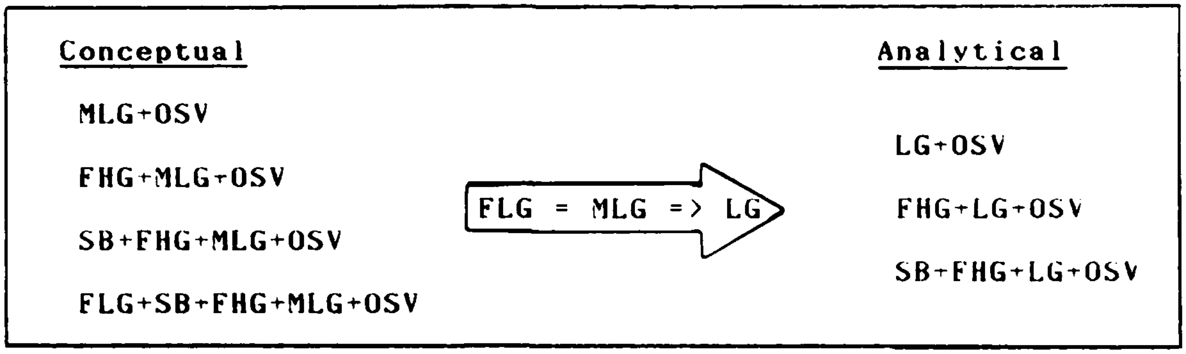
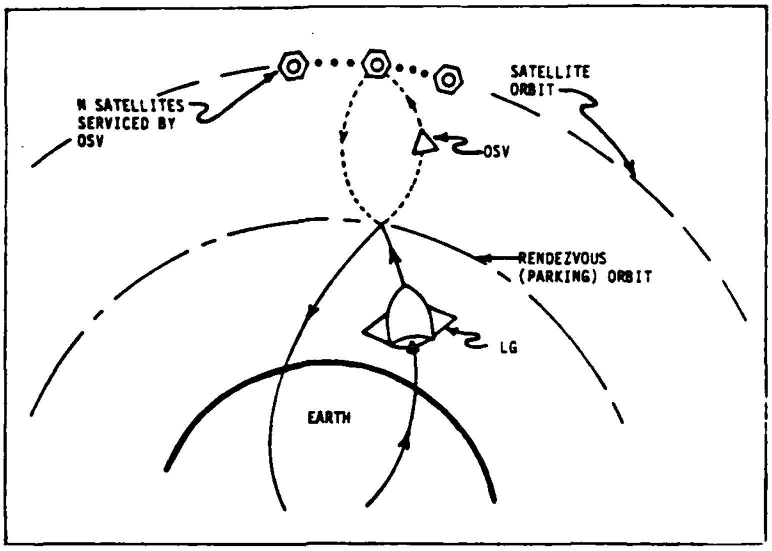


Figure ES.12 Conceptual and Analytical Models

The level of detail represented by the analytical equations is such that there is no distinction between a fixed or mobile low-G launch system. Both of these are then represented in the analytical equations by a generic low-G (LG) launch system. The four conceptual models collapse into the three analytical system models shown in the third column of Figure ES.12.

For each of the three analytical models, operating scenarios are defined to identify important system relationships to be represented by the equations. Physical realizations were generated for the LG+OSV analytical model. The scenario depicted in Figure ES.13 was used to derive the model equations.

LG-OSV SCENARIO



DESIGN CONSTANTS	DESIGN VARIABLES
BOTH OSV & LG	
FUEL Isp FUEL COST MASS TRANSFER RATE	NUMBER, PAYLOAD CAPACITY CONSUMED FUEL, MISSION RATE RELIABITLITY, STRUCTURE MASS
OSV UNIQUE	
TRANSFER RATE TO SAT CONSUMED PARTS/MISSION LIFE SUP/PERSON-TIME MASS OF GUIDANCE EQPT	CREW SIZE # SATS SERVED/MISSION MASS TO SAT/SERVICE # WAITING ORBITS
OTHER	**LG UNIQUE**
MAX TIME PEOPLE IN SPACE SAT SERVICE INTERVAL # OF SATS IN ORBIT SAT ALT.	# STAGES, # LAUNCH SITES DOWNTIME BETWEEN MISSIONS TIME BETWEEN LAUNCHES AT 1 SITE RENDEZVOUS ALT.

Figure ES.13 LG+OSV Scenario and Variables

The LG launches from earth to rendezvous with one or more OSVs. There the OSVs are refurbished and resupplied from the LG. The OSVs then depart on another servicing mission and the empty LG returns to earth for refurbishment and resupply. Notice some of the important constants in this model. For instance, the number and orbit of the satellites are fixed (at 144 and 800km), as well as the type of propulsion system (chemical, Isp = 500 sec). The model equations tie together these constants with the design variables to represent the interactions of the subsystems.

The design variables chosen, either directly or indirectly, affect the performance of the system. For instance, the number, payload capacity, and mission launch rate of each subsystem contribute to achieving a high mass delivery rate. A much more extensive description of these equations is the topic of Chapter IV, Volume II of this report.

With these equations, a candidate system (LG+OSV) has been modeled for further analysis. In the Systems Analysis step of the two phase methodology, the equations are used to generate, from an engineering viewpoint, a non-dominated solution set of physical system realizations.

ES.4.3 <u>Systems Analysis.</u> The purpose of the systems analysis step is twofold: (1) to generate a solution set

based on engineering requirements, and (2) to describe how good, in an engineering sense, that solution is. These two tasks will be referred to as "non-dominated solution set (NDSS) generation, and solution validation." Figure ES.14 depicts the information flow between the two tasks of the analysis step as it relates to the other parts of the SE methodology.

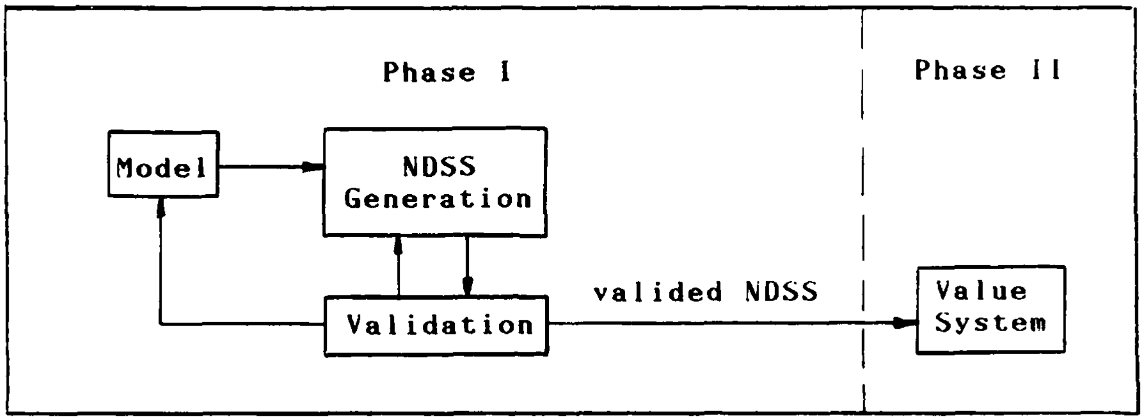


Figure ES.14 Analysis Step Information Flow

The model is the medium for generating the NDSS. The results of the validation task allow the analyst to determine if more iterations through the SE process may be necessary. Usually, this means either refining the model or changing the NDSS generating technique, after which an NDSS is again generated and checked for validity. This process is continued until the NDSS is validated. The final NDSS generated must be of sufficient detail to allow implementation. This marks the conclusion of Phase I of the

SE approach. The valided NDSS is then the input to the value system application (decision making) process of Phase II.

The method of generating the NDSS depends on the type, form and detail of the model. In the initial stages of the project the models may be simple word equations. The NDSS could be generated by a technique using pairwise comparison of the performance indicies (PI's). As the model becomes more complex different techniques, such as vector optimization, are applied. Except for simple problems, vector optimization solution generation techniques must be mechanized on a digital computer. The computer program PROCES (DeWispelare and Clark,1983) was used to generate the NDSS for this study.

Validation is the process of ensuring that the abstract representation (model) of the physical system behaves like the real system. The degree to which the model behavior matches the real system depends on the structure and detail of the model. Since the model is only an abstraction, the results obtained from it are only useful within certain limits. These limits depend on the areas of real system behavior that are of interest and the assumptions that are used during construction of the model. The focus of the validation task also varies as the project develops. Initially, the only concern may be realizability of the

solutions. In the more advanced stages of a project other factors, such as the sensitivity of the results to model parameter changes, become more important.

The Systems Analysis Step was performed on the LG+OSV satellite servicing system. The NDSS generated using this model had 69 members describing a wide range of LG+OSV system realizations. This set of pareto-optimal systems provides the decision maker with solutions in which the PI's cannot be improved without reducing the level of another PI. The rational decision maker will always choose from this set, and having it, he can explicitly examine trade-offs of his preferences between the objectives. The generation of this set is computer intensive, requiring the use of large computers such as a CDC Cyber 175. However, the set only needs to be generated once, since it is created using objective criteria.

The NDSS's validity was examined by several techniques. This analysis showed that the numerical optimization procedures used had generated a truly pareto optimal solution set. However, the analysis also showed that some of the solutions had design variables outside the valid range of application of the model. This problem was caused by the model simplifications for: manned versus automated servicing trade-offs, orbital transfer mechanics, and manned life support requirements. Finally, the dominant

behaviors of the model were identified. The model was most sensitive to the mass delivered per satellite service. due to its direct influence on one PI. and its indirect impact on the other PI's. The most important assumptions in the model were the parameters used to describe the satellite constellation being serviced.

ES.4.4 Decision Making. Every decision maker has a unique value system, which is simply a formal mathematical representation of his preferences. Having determined the decision maker's preferences, the analyst creates a weighted hierarchy of objectives from which a scalar figure of merit can be calculated for each system. The most desirable system is usually the system with the largest associated figure of merit.

The hierarchy of objectives in Figure ES.2 was shown to senior USAF decision makers from the USAF Space Division, the USAF Satellite Tracking and Control Facility, and the NASA (Carlton,1985; Crabtree,1985; Green, 1985; Hard, 1985; Janson, 1985; Lemon, 1985; Sundberg, 1985; Wimberly, 1985; Wittress, 1985; Zerson, 1985). Pairwise comparisons between objectives were solicited from the decision makers in personal interviews to be used in calculating their weightings to be applied to those objectives. Applying those preferences to the hierarchy of objectives, and calculating a single figure of merit for each system, a

ranking of systems can be established. Table ES.3 shows the hierarchy tree weightings and ranking of systems for the USAF decision makers identified. The best system is at the top of the ranking for each decision maker identified. Note however, that it is important to know how sensitive a particular solution is to changes in the decision maker's preferences.

Sensitivity analysis on the value system provides the decision maker with information about how robust a solution is to preference changes, and what solution would likely appear for a particular preference structure. A decision maker may be concerned about "selling" his choice of a solution to others (his boss, Congress, etc.), and therefore want a solution that stays highly ranked over a wide range of preference weightings. Alternatively, several decision makers may be involved in selecting a solution, and so a system that stays in a highly-ranked position over a wide range of preferences may be the best compromise. This requires examining system ordering characteristics as the preference weightings are varied.

Steps can be taken to identify which weighting values significantly change system ordering. These "significant" weighting values can then be used to represent those weighting values not identified, and the overall figure of merit is calculated for each system. Although some bias of

Table ES.3

Weightings and NDSS Rankings for Nine Decision Makers

		DECISION MAKERS								
		A	B	C	D	E	F	G	H	I
WEIGHTINGS	OVERALL COST WEIGHTING	0.5	0.88	0.88	0.17	0.50	0.75	0.14	0.87	0.50
	INITIAL COST WEIGHTING	0.25	0.17	0.50	0.25	0.14	0.83	0.87	0.90	0.83
	OPERATIONAL COST WEIGHTING	0.75	0.83	0.50	0.75	0.86	0.17	0.13	0.10	0.17
	OVERALL PERFORMANCE WEIGHTING	0.50	0.12	0.12	0.83	0.50	0.25	0.86	0.13	0.50
	RELIABILITY WEIGHTING	0.83	0.83	0.83	0.75	0.25	0.83	0.87	0.50	0.83
	MASS OF PAYLOAD DELIVERED WEIGHTING	0.17	0.17	0.17	0.25	0.75	0.17	0.13	0.50	0.17
	S	8	8	3	6	6	3	7	3	3
	Y	9	26	2	44	44	2	8	2	2
	S	2	25	8	52	52	8	9	4	7
	T	26	2	9	45	45	9	11	7	8
	E	25	9	10	22	53	7	28	10	9
	M	3	10	7	1	22	10	12	9	25
		7	3	25	53	1	25	29	8	26
	R	24	40	26	30	64	26	45	43	24
	A	12	39	24	15	15	24	27	63	27
	N	11	24	4	14	14	27	5	25	10
	K	5	23	23	17	17	4	2	26	23
	I	29	7	27	19	13	23	3	24	11
	N	23	12	40	18	18	40	22	27	12
	G	28	11	39	13	19	39	44	23	29
		27	5	43	16	16	11	1	62	28
		40	4	63	21	20	12	6	61	5
		39	29	12	41	30	63	24	50	39
		32	32	11	20	21	43	21	51	40
		47	35	5	65	41	29	26	42	42
		31	34	29	66	65	28	25	40	32
		10	36	28	28	33	5	15	39	60
		21	37	35	29	66	42	19	11	47
		15	38	34	5	5	50	14	12	67
		14	28	38	11	28	61	17	60	21
		17	27	36	12	29	51	18	29	20
		19	47	37	67	12	35	20	28	19

40	4	63	21	20	12	6	61	5
39	29	12	41	30	63	24	50	39
32	32	11	20	21	43	21	51	40
47	35	5	65	41	29	26	42	42
31	34	29	66	65	28	25	40	32
10	36	28	28	33	5	15	39	60
21	37	35	29	66	42	19	11	47
15	38	34	5	5	50	14	12	67
14	28	38	11	28	61	17	60	21
17	27	36	12	29	51	18	29	20
19	47	37	67	12	35	20	28	19
18	31	49	33	46	34	13	5	18
13	49	51	32	11	36	16	35	15
20	48	48	47	67	37	30	38	14
16	21	50	31	68	38	41	34	17
30	20	32	7	69	62	66	37	13
41	15	47	8	32	60	67	36	16
1	14	31	9	56	49	65	49	31
65	13	62	27	47	32	53	48	33
22	17	46	24	31	48	52	59	35
44	18	21	26	8	46	32	58	34
66	19	20	25	9	47	47	46	36
67	16	19	23	7	31	23	57	37
45	30	18	2	35	67	31	32	38
52	41	13	3	34	58	42	33	30
6	65	14	39	36	33	33	47	46
53	43	15	40	37	21	57	67	57
35	46	17	54	38	59	39	69	45
34	1	16	46	23	20	40	56	41
36	51	69	42	55	19	60	55	1
37	69	67	10	26	18	54	31	4
38	68	30	57	25	13	10	68	66
46	63	61	34	27	14	46	21	22
33	66	68	36	24	15	34	20	65
49	22	41	35	49	17	35	19	50
48	50	65	37	48	16	36	18	53
69	67	66	38	2	57	37	13	61
68	44	1	64	3	30	38	14	44
50	52	59	60	40	69	55	17	54
4	45	22	68	39	41	58	15	49
64	53	33	69	10	68	68	16	48
51	64	45	55	59	66	69	54	58
42	6	58	48	51	1	50	30	51
61	62	53	49	50	45	61	41	62
58	33	44	58	58	65	64	66	[illegible]
55	59	42	50	4	22	49	45	4
62	61	64	56	62	55	48	1	66
59	56	56	61	61	53	59	53	55

34	1	16	46	23	20	40	56	41
36	51	69	42	55	19	60	55	1
37	69	67	10	26	18	54	31	4
38	68	30	57	25	13	10	68	66
46	63	61	34	27	14	46	21	22
33	66	68	36	24	15	34	20	65
49	22	41	35	49	17	35	19	50
48	50	65	37	48	16	36	18	53
69	67	66	38	2	57	37	13	61
68	44	1	64	3	30	38	14	44
50	52	59	60	40	69	55	17	54
4	45	22	68	39	41	58	15	49
64	53	33	69	10	68	68	16	48
51	64	45	55	59	66	69	54	58
42	6	58	48	51	1	50	30	51
61	62	53	49	50	45	61	41	62
58	33	44	58	58	65	64	66	69
55	59	42	50	4	22	49	45	6
62	61	64	56	62	55	48	1	68
59	56	56	61	61	53	59	53	55
56	58	55	59	43	56	56	22	52
63	55	52	51	63	54	51	65	59
54	42	6	4	54	44	4	64	63
43	54	60	62	42	64	62	44	56
57	57	57	63	57	6	63	6	43
60	60	54	43	60	52	43	52	64

system ordering may be introduced for those weighting values not used in the figure of merit calculations, making reasonable assumptions can minimize the biases, and produce useful information for the decision maker.

ES.5 Conclusions

The two-phase approach is a useful method for solving complex problems, as shown in this study. It provides separation of the volatile decision making phase from the expensive, time-intensive engineering design phase. The engineering design phase generates an optimal set of design alternatives. This allows the decision maker to explicitly evaluate tradeoffs among the conflicting objectives without requiring a completely new engineering analysis for each tradeoff.

This methodology was applied to the evaluation of a LG+OSV servicing system. A NDSS was generated based on the critical attributes identified in the early value system design. The designs in the NDSS were arbitrarily numbered to assist in identifying individual designs. The preference weightings were then used to rank the members of the NDSS. Finally, a sensitivity analysis was performed to examine the behavior of the system rankings.

For the LG+OSV model, value system sensitivity analysis showed that system designs 2, 3, 6, 8, and 9 remained highly

ranked over a wide range of decision maker preferences. The design variables for systems 2 and 3 all have values within the valid range of the model at the current level of detail. Figures ES.15 and ES.16 show the physical characteristics of designs 2 and 3 respectively. Some of the design variables for systems 6, 8, and 9 are beyond the valid range of the model for this level of detail. and so they will not be dicussed further here. Volume II contains detailed descriptions of these and other designs in the NDSS.

System 2 would be selected if a decision maker preferred a system to have a high measure of reliability, but made little distinction in his preferences between minimizing operational versus initial costs. Figure ES.17 helps one visualize the conditions necessary for system 2 to be ranked in the "top" position.

System 3 would be selected if a decision maker preferred a system that minimized initial system costs. and also emphasized minimizing the overall system cost. Again. Figure ES.17 helps one visualize the conditions necessary for system 3 to be selected as the "top" system.

As noted above, systems 6, 8, and 9 all have design variables which take on values which are beyond the valid ranges of the model. Though they appeared in the highly

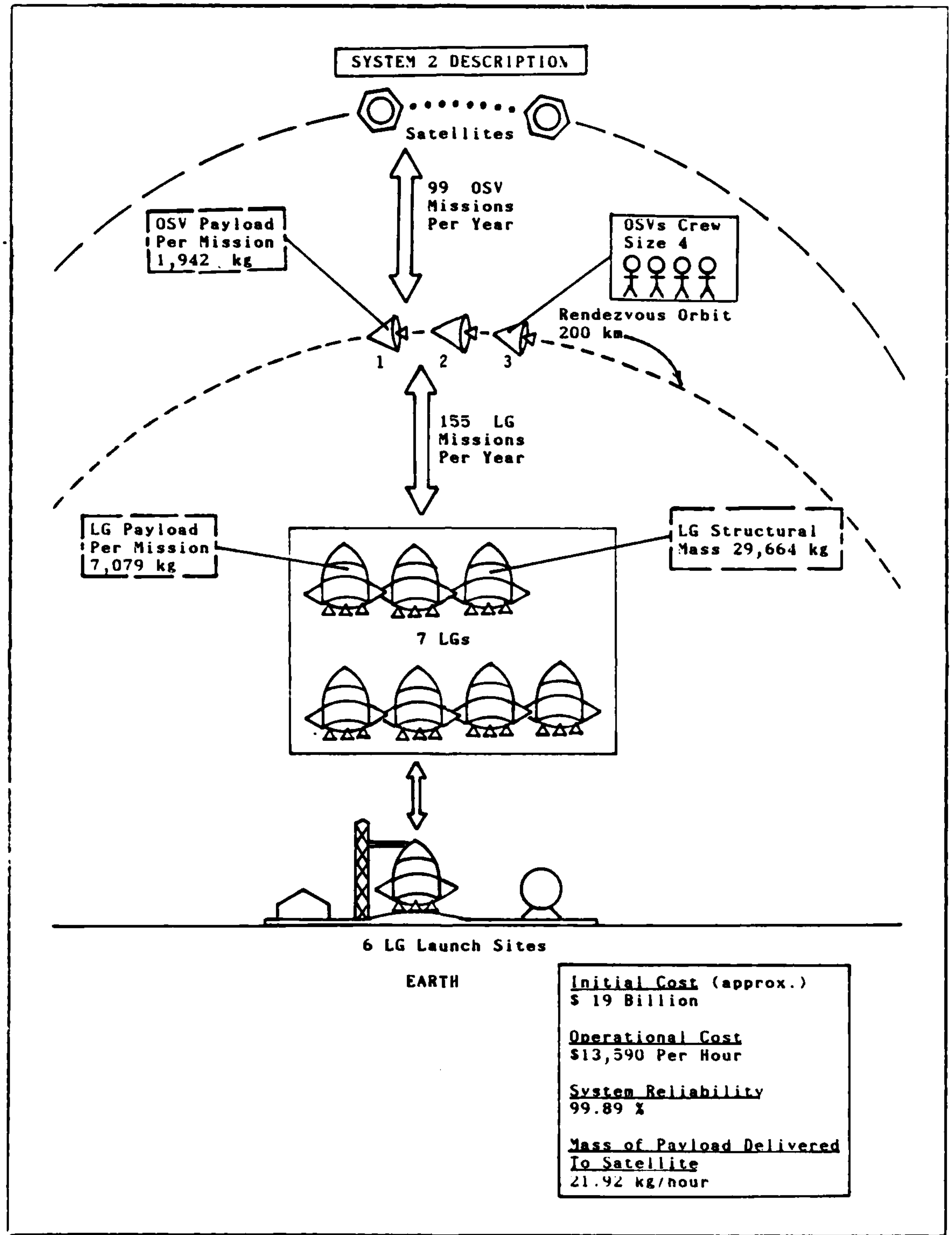


Figure ES.15 Physical Description of System 2

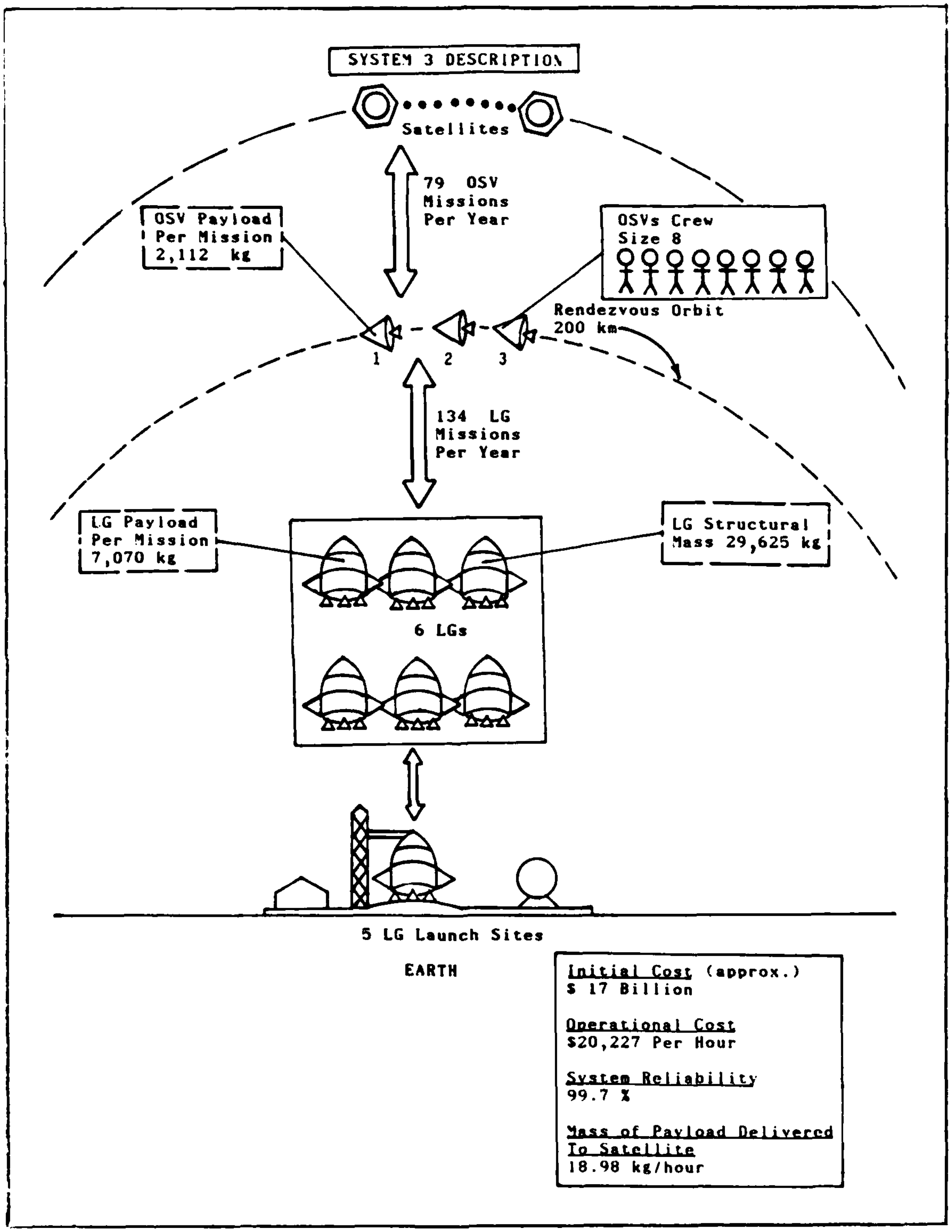


Figure ES.16 Physical Description of System 3

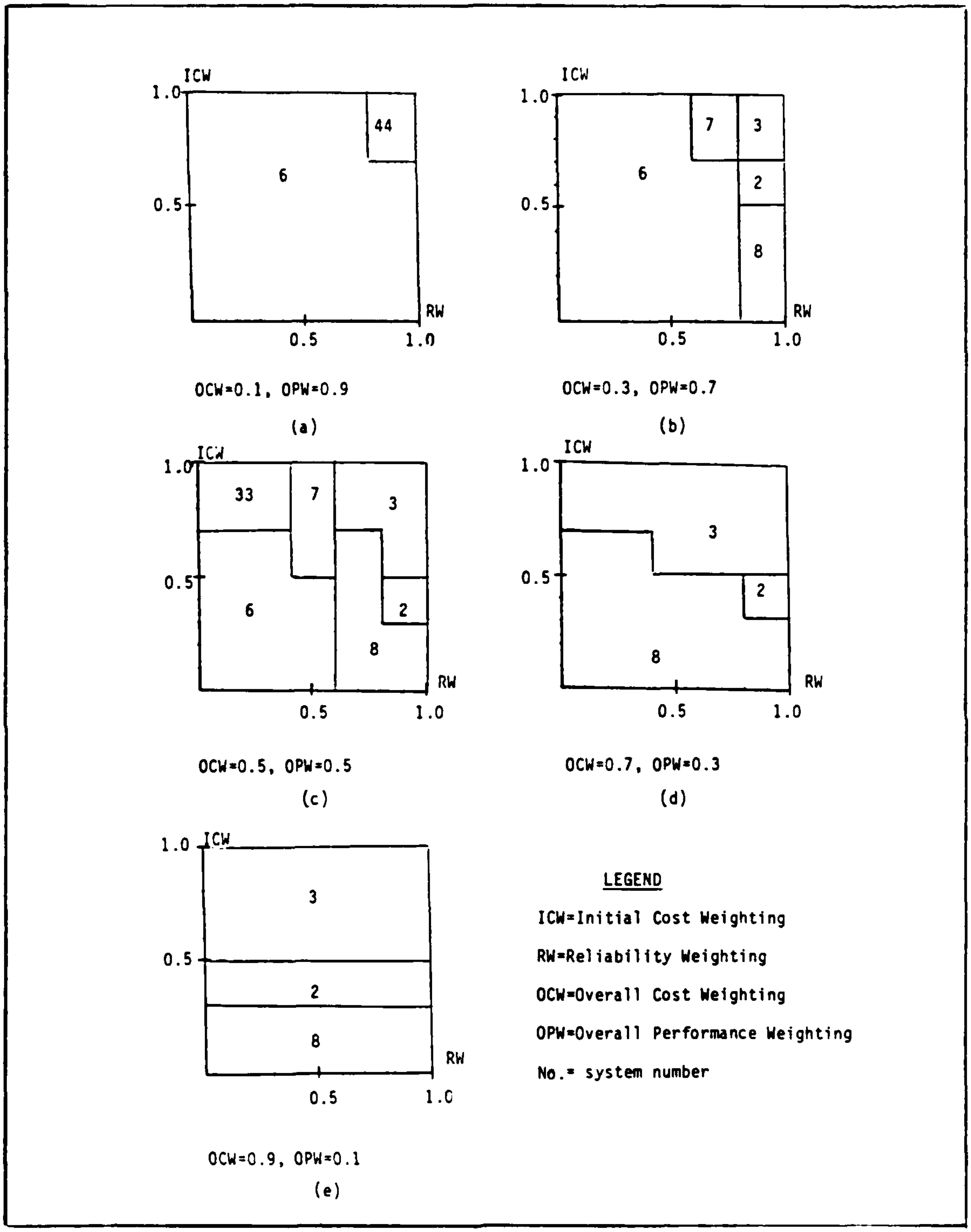


Figure ES.17 Preference Conditions for Systems 2 and 3 to Appear in the 'Top' Position

ranked positions, they are invalid designs and should not be used as the basis for further work.

ES.6 Recommendations

This study outlined a methodology to select a satellite servicing system and evaluated several initial system concepts. Future errorts to design and evaluate more detailed system concepts may build upon this study. The primary recommendation is to continue the application of the two phase systems engineering methodology to the alternative systems developed and modeled in the systems sysnthesis step. As these were preliminary models, there is insufficient detail to implement the systems identified, so additonal refinements of the model are necessary. These refinements should address inclusion of additional PI's, distinquish between ~~MLG's~~ and FLG's, improve the orbital mechanics relations, improve the representation of manned vs automated servicing, and improve the representation of life support requirements. Additionally, the value system needs refinement, such as incorporation of a more detailed objective hierarchy, and solicitation of high level decision maker preferences. For more details on each of these recommendations see Volume II of the report.

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VOLUME I - EXECUTIVE SUMMARY

A two-phase methodology for selecting an optimal military satellite servicing system is developed using the systems engineering approach. This methodology is used to evaluate several alternative systems at varying levels of detail. The candidate systems are composed of low-G launchers, high-G launchers, orbital servicing vehicles, and space bases. An optimal realization is then derived for a system of low-G launchers and orbital servicing vehicles. In the first phase of the approach, vector optimization techniques are used to vary the states of a model to obtain a set of optimal solutions. The second phase embodies the decision maker's preferences in a value system to enable preference ranking of the optimal solutions in the non-dominated solution set. This methodology, as presented, can be applied to any complex problem with multiple conflicting objectives. It is designed for use by an engineering organization supporting a senior-level decision maker.

The report is in three volumes. The Executive Summary (Volume I) is a cursory review of the study and is meant to be self-contained. The Final Report (Volume II) and the Appendices (Volume III) are more detailed and should be read together for completeness.

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